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Numerical Investigation of the Leakage Flow from a Pressurized CO_2 Pipeline

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Abstract

The accidental release of supercritical CO_2 is one of the main risks during the pipeline transportation for carbon capture and storage and enhanced oil recovery. The leakage of high pressure CO_2 involves phase transition and complex changes of the pressure and temperature fields in the pipelines. A mathematical method for simulating the leakage flow through a crack in a pressurized CO_2 pipeline is presented. The validated and accurate method has been employed to simulate the flow inside the pipe, while the leakage flow through the crack was calculated using a capillary tube assumption. In the numerical simulation, a real gas equation of state was employed instead of the ideal gas equation of state. Moreover, results of the flow through the crack and measurement data obtained from laboratory experiments of pressurized CO_2 pipeline leakage are compared for the purpose of validation. The pipeline pressure and the leakage flow rates are analysed, which reveal the complex nature of the leakage flow of supercritical CO_2 pipeline transport.

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Keywords: CO_2 pipeline transport; choked flow; flow through a crack; numerical simulation; release pressure

1. Introduction

The use of high pressure transmission pipelines to convey carbon dioxide in the dense phase mostly in the supercritical phase is regarded as an essential element of the development of carbon capture and storage (CCS) and enhanced oil recovery. It is foreseen that large amounts of CO_2 will be transported as CCS will be deployed on an industrial scale [1]. Many pipeline failures caused by stress corrosion or decaying are initiated from small punctures or orifices [2]. In order to detect and control the risks of these

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accidental failures in early stage, it is pivotal to understand and to be able to predict the leakage flow characteristics including the mass outflow rate, the flow pressure.

The majority of the pipeline outflow models in the numerical investigation of accidental release from high pressure hydrocarbon pipelines are based on the homogeneous equilibrium mixture (HEM) [3] or the homogeneous relaxation model (HRM) [4]. For single-phase and two-phase flows, the choked flow condition in the model is determined by maximizing the release mass flow rate with respect to the release pressure [5], which may be more justified for full bore rupture of the pipeline in consideration of the almost instantaneous pressure drop at the rupture plane. However, in the case of small puncture or orifice the choked flow condition is much more complex, and meanwhile the pressure and temperature may vary violently along the fracture. The detailed parameters such as escape velocity, exit pressure and temperature need to be well determined when assessing the pipe safety or modelling the vapor dispersion. Moreover, there are studies in the rapid expansion of supercritical solution solving the governing equations numerically, which calculate the choked flow from a stagnation source to the capillary exit [6]. In this study, a one-dimensional fluid flow model was developed to study the leakage flow behaviour and the results were compared with the data obtained from an existing laboratory facility.

2. Experimental setup

This section describes the experimental setup and the leakage experiments performed at the University of Science and Technology of China [7]. Figure 1*a* shows the test section of a high pressure CO_2 circulation pipeline system. The test section is 10m long and possesses a carbon steel pipe with a 0.04m outer diameter and 0.03m inner diameter (1). In the middle of the pipe, there is a short "side tube" with a release orifice (4) for controlling the initiation of the leakage, and the cross-section view of this leakage module is shown in Fig.1*b*. In each experiment, the CO_2 was pressurized and cooled down to achieve a high pressure liquid phase, and then be injected into the pipe, and be heated or pressurized by a pump to maintain a specific equilibrium pressure, temperature and phase conditions. In the decompression tests, the pressure of the fluid and the temperatures of both the fluid and the wall were all measured with pressure transducers and thermal couples as schematically shown in Fig. 1*a*. Table 1 summaries the three experiments performed using a release orifice diameter of 1 mm.

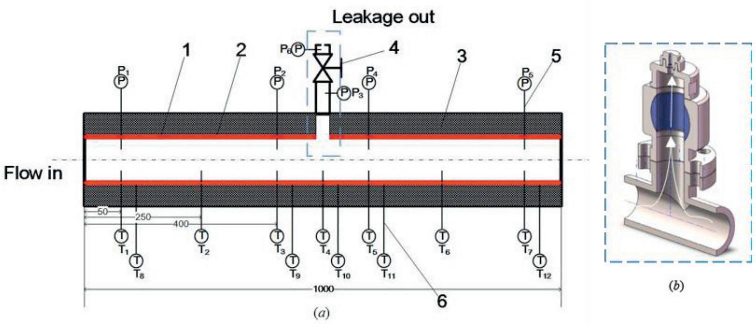

Fig. 1 (*a*): overview of the 10 m long test section pipeline for experimental study of CO_2 release, the main sensors and key geometry aspects are schematically indicated and described below. (*b*): the cross-sectional view of the leakage module.

Table 1. Operating conditions and initial parameters in experiments.

Properties	Test 1	Test 2	Test 3
Initial Pressure (MPa)	8.93	7.01	4.96
Temperature (°C)	40.9	40.0	39.8
Phase state	Supercritical	Subcritical	Gas

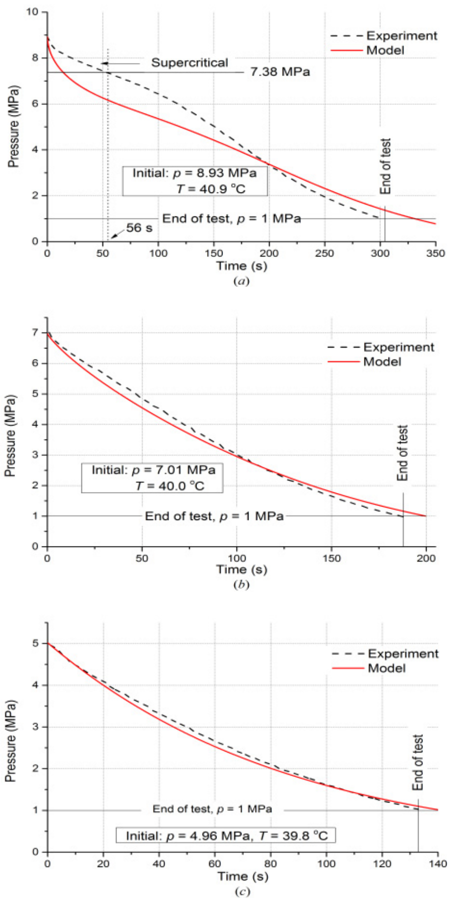

Fig. 2 Time variation pressure measured in Test 1, 2 and 3 in comparison with the prediction using the vessel blowdown model and capillary tube assumption.

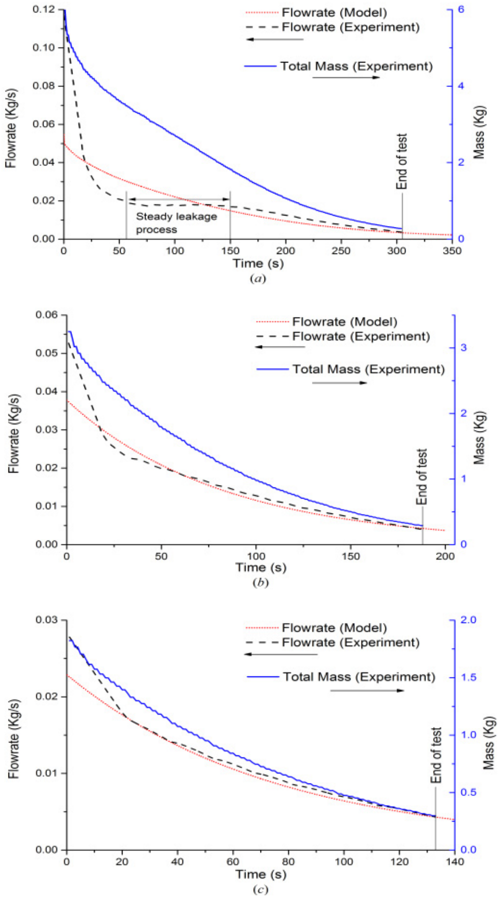

Fig. 3 Time variation of total mass of CO_2 in the pipeline measured in Test 1-3, and the mass flow rate calculated in comparison with prediction using the model.

3. Theoretical approach

For short pipeline or reservoirs with small orifice, the blowdown model can be used to simulate the decompression process [5], which can be considered as a zero-dimensional pipeline release model where the momentum of the fluid upstream the release point is neglected. Inside the release pipe, the HEM is adapted in which assumption of local thermodynamic equilibrium and isentropic flow is adopted. The density is calculated by a mass balance and energy balance. To calculate the thermodynamic properties of the vapour or liquid fluid formulation during the decompression process, the Peng-Robinson (PR) equation of state is employed. This equation has been shown to be particularly applicable to high pressure hydrocarbon mixtures. It is assumed that the pipeline leaks at time $t = 0$, choked flow is formulated in the release point momentarily. With respect to that crack geometry structure, the cross-sectional area of the orifice does not have a convergent configuration, so that a capillary tube assumption for the leakage module is employed which has been used likewise in the rapid expansion of supercritical solution [6]. For the capillary, the typical analysis involves the quasi-one-dimensional (QOD) approximation including viscous frictional effects. Unlike the convergent nozzle model in which the area change dominates the acceleration to sonic conditions, the capillary flow is not isentropic. In this study, the heat transfer in the capillary tube is neglected and the flow is considered as adiabatic, and it is referred to quasi steady state.

4. Results and discussion

Figs. 2 and 3 show both the experimental results in Table 1 and the corresponding simulating results of the pipeline pressure and the mass flow rate calculated as functions of time. While in Test 1 the fluid is initially in supercritical state, in Test 2 initially in a near critical but subcritical state and initially from a gas-like phase in Test 3. In particular, Fig. 2*a-c* presents the variation of the pipeline pressure measured in Tests 1, 2 and 3 in comparison with the prediction using the vessel blowdown model and capillary tube assumption. Fig. 3*a-c* show the time variation of the total mass of CO_2 in the pipeline measured in the three tests. As can be seen, all the three predictions are in good agreement with the experimental data.

5. Conclusion remarks

This paper presented a numerical method to evaluate the leakage flow rate through a nozzle in the pipe. The method has been applied to single-phase flow, where direct comparisons to experimental data are of good agreement. The pipeline decompression model based on the HEM assumption and the blowdown model was further incorporated with a capillary tube assumption calculating the choked flow condition. The choked flow calculated based on the assumption depends only on the pressure and temperature in the inlet boundary and meanwhile the PR equation of state was applied, which means the model can be easily extended to two-phase flow simulation in a straightforward manner. The proposed model also accounts for the effects of heating and viscous friction at the pipe wall. The good agreement between the simulation and experimental results indicates that the model can be effectively used to predict the leakage flow characteristics.

Reference

[1] Metz B, Davidson O, de Coninck H, Loos M, Meyer L. IPCC special report on carbon dioxide capture and storage. C. Cambridge University Press, UK 2005: p. 181-185.
[2] Lilly MT, Ihekwoaba SC, Ogaji SOT, Probert SD. Prolonging the lives of buried crude-oil and natural-gas pipelines by cathodic protection. *Appl Energ* 2007; **84**(9):p. 958-970.
[3] Oke A, Mahgerefteh H, Economou I, Rykov Y. A transient outflow model for pipeline puncture. *Chem Eng Sci* 2003; **58**(20):p. 4591-4604.
[4] Brown S, Martynov S, Mahgerefteh H, Proust C. A homogeneous relaxation flow model for the full bore rupture of dense phase CO2 pipelines. *Int J Greenh Gas Con* 2013; **17**:p. 349-356.
[5] Martynov S, Brown S, Mahgerefteh H, Sundara V, Chen S, Zhang Y. Modelling three-phase releases of carbon dioxide from high-pressure pipelines. *Process Saf Environ* 2013; **PSEP-379.**
[6] Khalil IG, Miller DR. The Free-Jet Expansion of Supercritical CO_2 from a Capillary Source. *AIP Conference Proceedings* 2005; **762**(1):p. 343-348.
[7] Xie QY, Tu R, Jiang X, Li K, Zhou XJ. The leakage behavior of supercritical CO_2 flow in an experimental pipeline system. *5th International Conference on Applied Energy*. Pretoria, South Africa. 2013.

Biography

Xuejin Zhou is currently undertaking his PhD in University of Science and Technology of China. His research has been mainly focused on numerical modelling of multiphase flow with application in carbon capture and storage and parallel computing.